Renewable and Sustainable Energy Reviews 15 (2011) 2322–2329

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Renewability of wind power in China: A case study of nonrenewable energy cost and greenhouse gas emission by a plant in Guangxi

G.Q. Chen[a,*], Q. Yang[a,*], Y.H. Zhao[b]

[a] State Key Laboratory of Turbulence and Complex Systems, College of Engineering, Peking University, Beijing 100871, PR China
[b] China Huadian Engineering Co., Ltd., China Hua Dian Corporation, Beijing 100035, PR China

ARTICLE INFO

Article history:
Received 31 August 2010
Accepted 27 January 2011

Keywords:
Fossil energy cost
Greenhouse gas emission
Wind farm

ABSTRACT

The high degree of renewability of wind power in China is illustrated by a case study of nonrenewable energy cost and greenhouse gas emission to a typical wind farm in Guangxi. The account for the life cycle of components manufacturing and transportation, installation, operation, maintenance, disassembly and disposal is based on the embodiment intensities of nonrenewable energy use and greenhouse gas emission by an environmental extended input–output analysis for typical commodities in the Chinese economy. The nonrenewable energy cost and greenhouse gas emissions are estimated, respectively, as 0.047 MJ and 0.002 kg CO_2-eq for 1 MJ of electricity by the wind farm plant, respectively 56 and 108 times less than those of the average coal plant in China. Considering the dominance of coal power, the nonrenewable energy saving is estimated at 1.22E+10 MJ during its 20 years operating period, while the reduced greenhouse gas emissions are 1.03E+09 kg CO_2-eq by the wind farm studied. Compared with the study of the wind farms worldwide, the nonrenewable energy cost intensity of Chinese 1.25 MW wind turbines is in the median range, and the GHG emission intensity is at the lower end of the scale. The concrete results have essential policy making implications supportive to a further spread of wind power technology in China.

Contents

1. Introduction

In Chinese history, the utilization of wind power can be traced back to at least 1800 years ago in the East Han Dynasty, when people started to hoist the sail and transport goods by wind. In modern times, merely in the Jiangsu Province, there used to be more

* Corresponding authors. Tel.: +86 10 62767167; fax: +86 10 62754280.
E-mail addresses: gqchen@pku.edu.cn (G.Q. Chen), yq@pku.edu.cn (Q. Yang).

1364-0321/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.rser.2011.02.007

than 200,000 wind power water pumping machines in operation [1].

Wind farm construction had started in China since the mid 1980s [2]. For promoting the national wind power development, the former Ministry of Electrical Power issued *Opinions on Wind Power Farm Construction and Management* in 1994, in which, all power grids were asked to purchase all electricity generated by wind farms, and the purchasing price should be set capable for the repayment of principal and interest rates plus a reasonable profit. In 1999 the Chinese Government issued the *Notice on Several Problems for Promoting Renewable Energy Development*, in which, certain favorable policies for power generation by renewable energy in particular by using wind energy have been set forth, including 2% bank loan discount from government subsidy and 5% interest rate return on investment for those wind power projects using domestic wind power equipment [3]. In order to promote the commercialization of wind power, the National Development and Reform Commission (NDRC) adopted a concessional approach in 2003 with a 20-year operational period. This was to select potential projects of relatively large scale (100 MW), and to choose the investor through competitive bidding [4]. China's Renewable Energy Law came in force in January 1, 2006, which requires that power grid operators must purchase a full amount of wind power generated by registered producers, and also offers financial incentives, such as a national fund to foster renewable energy development and discount lending and tax preferences for renewable energy projects [5]. After nearly 30 years of development, 21,581 wind turbines have been installed in the mainland, with a total installed capacity of 25,805 MW by the end of 2009 [6]. According to the national Long- and Medium-term Plan on Renewable Energy, the total existing capacity of wind power will be up to 30 GW by 2020 in China [7]. Nowadays, the original goal of 30 GW installed capacities in the year 2020 has already been achieved ahead of schedule [8]. The manufacturing technologies have advanced and production capability of wind power equipment has been greatly increased, as well as wind power management skills having been improved in China. More than 90% of 750 kW wind turbines are domestically manufactured. Many experts believe that China will be the center of the global wind energy market in the future [9]. The 1.25 MW wind turbine studied in this paper is also made in China.

Recently various approaches based on energetic or exergetic methods to assess the renewability of energy conversion systems, especially the renewable energy conversion system, have been proposed [10–16]. The simplest is a binomial approach that classifies it as either "renewable" or "nonrenewable" [11]. Considering the huge increase and expected future growth of wind power, the measurement of renewability of wind farm systems, which consume both renewable wind kinetic energy and nonrenewable energy sources associated with provision of various inputs for the construction and maintenance of the system, has become of supreme importance recently. Wind energy, a relatively large energy source globally, is being investigated in various countries as a potentially significant renewable resource. As for wind farms, many researchers have considered the environmental benefits of wind turbines, to ensure that they provide a net energy benefit and remediation of greenhouse gas (GHG) emissions, in the pursue of sustainable development of wind harnessing industry. In 2002, Lenzen and Munksgaard [17] carried out a worldwide survey of the previous studies of others on environmental performances of wind farms. The authors showed that "despite the fact that most modern wind turbines differ little over a wide range of power ratings with regard to their material consistency, there is a relatively large variation in energy and CO_2 intensities". For the past few years, Martin et al. [18] performed a comprehensive system analysis of the possible CO_2 reduction of an offshore wind power in Germany. Ardente et al. [19] conducted a life cycle assessment of an Italy wind farm. Similarly, Martínez et al. [20] made a life cycle assessment study quantifying the overall impact of an onshore wind turbine and each of its components in Spain. Tremeac and Meunier [21] have evaluated the energy demand and GHG emissions for a 4.5 MW and a 250 W wind turbine in France. Meanwhile, Crawford [22] presented the results of a life cycle energy and GHG emissions analysis of two wind turbines based on hybrid embodied energy analysis and also considered the effect of wind turbine size on energy yield. Recently, by viewing 119 wind turbines from 50 different analyses, ranging in publication date from 1977 to 2007, Kubiszewski et al. [23] distinguished between important assumptions about system boundaries and methodological approaches. However, no study on fossil energy cost and GHG emissions of Chinese wind farm can be found in publications, though extensive research on various renewable energy sources and systems in the society have been performed [24–43].

This paper aims to evaluate the renewability of wind power in China by a case study of nonrenewable energy (NE) cost and GHG emissions of a typical wind farm in China, located in Guangxi. It takes into account nonrenewable material and energy flows and associated GHG emissions over the whole production process starting from wind turbines manufacturing, wind farm construction, operation and maintenance, and lastly to its disassembly and disposal. The analysis of the study maps nonrenewable energy flows and GHG emissions in fine detail and thus helps identify nonrenewable energy intensive components. The results are compared with other new renewable energy plants in the world, and also with traditional coal power plants in China. The study provides useful information for Chinese electrical companies in decreasing the nonrenewable energy cost of their wind farms and in minimizing the GHG emissions due to the construction of new plants or dismantling of old ones. Also essential policy making implications supportive to a further spread of wind power technology in China is provided.

2. Methodology

In theory, a totally renewable energy would involve no fossil energy requirement. In fact, renewable energy systems require both renewable and nonrenewable energy inputs. Systems indicators are essential in physical assessment of renewable and sustainable energy technologies [42]. Within energy analysis, most remarkable is the basic concept of energy return on investment (EROI), defined as the ratio of the energy extracted or delivered by a process to the energy used directly and indirectly in that process [44]. The reciprocal of EROI has been recently addressed by Chen and Chen [45] as an energy cost indicator to denote how many energy times of cost used in the whole manufacturing process over the energy are contained in the final product. While energy efficiency indicated by EROI remains interesting, it does not suffice to evaluate nonrenewable energy's contribution to the fabrication of presumed renewable energies. Fossil energy ratio, defined as the ratio between the biofuel energy content and the fossil energy input, has been used to identify whether a biomass derived fuel is renewable [15,46]. For nonrenewable energy use associated with its believed dominant role in the climate change, an appropriate evaluation should address how much nonrenewable energy instead of inclusive energy is consumed to produce a presumed renewable energy. It is appropriate to use nonrenewable energy investment in energy delivered (NEIED) expressed as

$$\mathrm{NEIED} = \frac{\mathrm{NE}}{E_{\mathrm{out}}} \tag{1}$$

where NE is the nonrenewable energy used directly and indirectly in the production process, and E_{out} is the net electricity to access

grid for wind power. NE can be calculated as

$$NE = \sum NE_i = \sum (Input_i \times C_i) \tag{2}$$

where NE_i denotes the nonrenewable energy used directly and indirectly in the production of the ith inputs $Input_i$ to the whole chain of a wind farm. And to calculate the proportion of the unit primary nonrenewable energy demand directly and indirectly in the production or preparation of the ith input, C_i is defined as the nonrenewable energy-intensity coefficient of the ith input. Such coefficients can be measured by one of two general methods: namely process analysis or input–output (I–O) analysis. Both methods require the same data and would yield the same result if a fully disaggregated data base were available.

NEIED in terms of how much nonrenewable energy is expended to convert the kinetic energy of wind to generate per unit electricity is devised to identify the renewability of presumed renewable energies. The more nonrenewable energy required to produce the electricity, the less we can say that this wind electricity is renewable. Significant cases could be identified for different ranges of NEIED values. NEIED < 1 is for a renewable process in which more energy is produced than NE invested, while NEIED > 1 is for a nonrenewable process in which more NE is consumed than energy produced.

Similarly, the GHG emissions associated with NE cost can be calculated as

$$GHG = \sum GHG_i = \sum (\mathrm{Input}_i \times G_i) \tag{3}$$

where GHG_i denoting the direct and indirect GHG emissions in the production of ith inputs, G_i is defined as the GHG-intensity coefficient of the ith inputs.

In this study, most of the nonrenewable energy intensities are evaluated by subtracting renewable energy inputs into the society in an environmental extended I–O analysis which is performed by Zhou [47], with embodiment intensities for all the 151 kinds of typical commodities in Chinese economy conclusively provided as a systematic account of embodied ecological elements in the Chinese national economy. GHG-intensity coefficients can also be found in Zhou [47]. In addition, because the wind tower foundations cover only a small area of land, the GHG emissions linked to land use change is ignored in this study. And due to the data unavailability, possible emissions from the foundation into the environment have not been considered during the lifespan of the wind turbine.

3. Case study

The concerned wind farm locates in the Darong Mountain Resort (110°11′26″E–110°15′23″E, 22°51′36″N–22°52′49″N) in Yulin City, Guangxi Zhuang Nationality Autonomous Region, China, and covers a surface area of 8.0 km^2. No buildings were constructed in the area which is near by the main peak of Darong Mountain (height of 1350 m). The vegetation is constituted by spontaneous grass and small shrubs. The physical geological appearance is in favorable condition, and no collapse and landslides occurred during recent years. The scheme proposes the installation of 24 wind turbines each with a generating capacity of 1.25 MW, a hub height of 68 m and a blade diameter of 64 m (total height 100 m). Each wind turbine tower is connected to a 35 kW box-type transformer. The tower is installed on flat lay-bay and is firmly anchored with a 3.3 m foundation. A substation with a 110 kV step-up transformer is constructed to decrease the line loss. The control system is also located in the substation. Taking one year to construct, the project is designed with an operational life of 20 years.

There are 24 wind turbines with a total installed capacity of 30 MW. The annual average wind speed is 7.0 m/s at a height of 55 m. Based on the characteristic power curve and hourly wind data for location of the wind farm, the annual gross energy output of the 24 wind turbines is calculated to be 6.54E+07 kW h. Thus the annual electricity to access grid for each turbine will be 2.72E+06 kW h with an availability of 2179.5 h per year on average. All of the detailed data referring to the wind farm are from sources provided by the developer, China Hua Dian Corporation [48].

Table 1
Components of per wind turbine.

Component	Sub-component	Materials	Quantity (t)
Rotors	Three blades and nose cone	Resin	6.6
		Fibre glass	4.4
	Blade hub	Cast iron	7.9
Nacelle	Bed frame	Iron	11.4
	Main shaft	Steel	6.6
	Transformer	Silica	0.2
		Steel	3.6
		Copper	1.6
	Generator	Silica	0.2
		Copper	2.2
		Steel	4.6
	Gearbox	Iron	8.7
		Steel	8.7
	Nacelle cover	Fibre glass	0.9
		Resin	1.3
Tower	Plates steel	Steel	87.9

The wind farm performance was studied in six major parts, namely:

(1) wind turbines components (rotors, nacelle, tower, and their sub-components);
(2) substation components (transformer and control system);
(3) transport;
(4) building works (tower foundations, substation foundation, etc.);
(5) operation and maintenance;
(6) disassembly and disposal.

3.1. Wind turbines

The mass of used materials to manufacture turbines has been assessed on the basis of suppliers' technical reports and maintenance handbooks. The manufacture of the turbines can be decomposed into the manufacture of the three main parts: the rotor, the nacelle and the tower. Table 1 shows the detailed survey of wind turbines' components. The whole turbine weighs approximately 156.8 t. The rotor is composed of three blades, the hub and the nose cone. Each blade is 31 m long, weighs 3.6 t and is made of fibre glass and resin material. The nose cone weighs 0.2 t and is made of the same material as the blade. The blade hub is made of cast iron, which weights 7.9 t. The total masses of materials utilized in nacelle manufacturing are 20.1 t iron, 23.5 t steel, 0.4 t silica, 3.8 t copper, 0.9 t fibre glass and 1.3 t resin. The tower is made of plates of steel and it has been assumed that the tower is made of 100% steel. The installation of wind towers is generally carried out by cranes and other specialized construction machines.

3.2. Substation

A substation is constructed with a 110 kV step-up transformer and the control system of the wind farm. The 110 kV step-up transformer is designed to decrease the line loss. The control system mainly consists of five computers (Table 2).

Table 2
Components of substation.

Component	Materials	Quantity
Transformer	Silica	0.6 t
	Steel	10.8 t
	Copper	4.8 t
Computers		5

3.3. Transportation

Yulin City is crossed by Nanwu highway and No. 324 national highway. All of the equipment is firstly transported from the manufacturer to Yulin City on the highway by diesel vehicles, and then from Yulin City to Darong Mountain, a distance of 40 km. Wind rotors are produced in Shanghai, which is 2185 km away by land transportation from Yulin City. Transformers are fabricated in Nanjing City with a distance of 2103 km far away from Yulin City. The steel bar for wind towers is purchased in Yulin City. The consumption intensity of the diesel is estimated as 0.05 L/(t km). Diesel density is 0.83 kg/L. All these data indicate a diesel fuel consumption of 344,252.9 kg for the transportation.

3.4. Building works

Building works mainly includes the construction of tower foundations and substation. The tower foundation is made on site and consists of filling up a 3.3 m deep hole (typical in a regular octagon with a 14.0 m diameter for its inscribed circle) with some concrete reinforced by steel: the total amount of reinforced concrete for all of the 24 towers is 8333.6 m^3. Including the construction of substation, the building work in all has a volume of 8497.4 m^3 of concrete and a total weight of 999.9 t of steel for the reinforcing bars. In a three months' peak construction period, the power consumption load is 2000.0 kW h/day, and the water consumption of 300.0 m^3/day is supplied by a reservoir about 1 km away from the wind farm (Table 3).

3.5. Operation and maintenance

The auxiliary power consumption and line loss together accounted for 6% of the gross generation, which will be subtracted in the calculation of net electricity to access grid from the wind farm. 12 Permanent personnel are employed in the plant daily operation with a daily tap water consumption of 3.5 m^3. Since maintenance is mainly transportation of the personnel to the site for regular check up of the turbines, the fuel consumption is mostly dependent on the distance of traveling. However, because the data of the travel distance associated with each check up process are not available, the related fuel consumption is ignored in this study. Also, the electrical company has scheduled semi annual maintenance, which mainly implies lubrication, painting and substitution of spare parts as established in the maintenance handbooks. During the average useful life of a wind generator, it is supposed to substitute one blade and 15% of generator's components [19].

Table 3
Inventory of nonrenewable inputs in building works.

Item	Materials	Quantity
Tower foundations	Concrete (m^3)	8333.6
	Steel bar (t)	992.0
Substation	Concrete (m^3)	163.8
	Steel bar (t)	7.9
Power supply	Electricity (MW h)	180.0
Water supply	Reservoir water (t)	27,000.0

3.6. Disassembly and disposal

The plant's disassembly and disposal is unpredictable. No completely detailed data are available regarding the Yulin wind farm case. A scenario has been depicted based on the studies by other research as follows:

Rotors and nacelle: 20% of blade materials would be recycled [19] and other components will be sent to the dump nearby.
Tower: the material undergoes a recycling process in which losses of material are estimated at 10% [49]. An average material loss rate of 10% has been assumed for the recycling process.
Substation: 3% of the computers components [50] and the 10% of the transformer materials would be usable in the recycling process [20].
Foundations: it has been assumed that the foundations will be left in place and covered with a layer of 20–30 cm of organic soil [20,51].

4. Results and discussions

4.1. Results

As for the wind power life cycle, NE cost and GHG emissions are listed in Table 4.

The total NE cost for the 20 years wind farm is summed up to be 2.21E+08 MJ. As described in Section 3, the annual electricity output to assess grid is 6.54E+07 kW h. Then, NEIED is evaluated as 0.047, indicating that wind power requires 0.047 units of nonrenewable energy to generate 1 unit of electricity, and revealing a high renewability of the process. Dividing total NE cost by the electricity to access grid net, payback period for the energy investment has been found as 0.94 year. Analysis of the results of Table 4 shows that wind turbines (40.5%) and the building work (49.7%) are the two single largest contributors, which together take up 90.2% of the total NE cost of this wind farm (see Fig. 1). As for the building work, the tower foundation makes up the largest proportion of NE cost of this part, at 97.9%; Power and water supply have a low incidence (2.1%). As for the components of wind turbines, rotors account for the largest proportion of this part, at 49.3%. Nacelles represent 43.0%, while the towers represent only 7.7% of this part.

Accounting of GHG emissions caused due to manufacturing and operation of the wind farm has been done in a way similar with the NE analysis (see Table 4). The total GHG emissions for the 20 years wind farm operation are summed up to be 9930.0 t CO_2-eq. An embodied GHG emission of 0.002 kg CO_2-eq/MJ is found for the wind farm. Fig. 2 shows that 68.8% of the total GHG emissions are caused in the building works, as well as 27.1% in the manufacture process of components of wind turbines. The GHG emissions embodied in the operation and maintenance stage take up only 3.5%. As for the building work, tower foundations is the most fossil energy intensive mainly because of the use of steel bars (30.6% of this part) and concrete (67.1% of this part). As for the components of wind turbines, nacelles account for the largest proportion of this part, at 56.4%, while the rotors and towers represent 32.3% and 11.3%, respectively.

The percentages of NE cost in terms of the transportation and substation are no more than 1.0%. Also the percentages of GHG emissions in terms of the transportation and substation are less than 1.0%. Then the estimation uncertainties associated with these inputs are not significant for the overall assessment.

4.2. Comparison with other wind farms

Despite the fact that the structure and technology of most modern wind turbines differs little over a wide range of power ratings,

Table 4
NE cost and GHG emissions of a Chinese wind farm.

Item	Materials	Quantity	Unit	NE intensity (MJ/unit)	GHG intensity (t CO_2-eq)	NE (MJ)	GHG (t CO_2-eq/unit)
Wind turbines							
Rotors	Resin and fibre glass	2.6E+02	t	1.88E+05	3.07E+00	4.96E+07	8.10E+02
	Cast iron	1.9E+02	t	2.93E+04	1.25E+00	5.56E+06	2.37E+02
Nacelles	Iron	4.8E+02	t	2.93E+04	1.25E+00	1.41E+07	6.03E+02
	Steel	5.6E+02	t	3.26E+04	1.39E+00	1.84E+07	7.84E+02
	Silica	9.6E+00	t	3.06E+04	6.00E−01	2.94E+05	5.76E+00
	Copper	9.1E+01	t	1.64E+05	4.70E+00	1.50E+07	4.29E+02
	Resin and fibre glass	2.2E+00	t	1.88E+05	3.07E+00	4.14E+05	6.75E+00
Towers	Steel	2.1E+03	t	3.26E+04	1.39E+00	6.88E+07	2.93E+03
Substation							
Transformer	Silica	6.0E−01	t	3.06E+04	6.00E−01	1.84E+04	3.60E−01
	Steel	1.1E+01	t	3.26E+04	1.39E+00	3.52E+05	1.50E+01
	Copper	4.8E+00	t	1.64E+05	4.70E+00	7.87E+05	2.26E+01
Computers		5.0E+00		9.60E+03	2.50E−01	4.80E+04	1.25E+00
Transportation							
	Diesel	4.3E+01	t	4.67E+04	4.50E−01	2.02E+06	1.95E+01
Building works							
Tower foundations	Concrete	8.3E+03	m^3	6.03E+03	5.30E−01	5.03E+07	4.42E+03
	Steel bar	9.9E+02	t	5.63E+04	2.03E+00	5.58E+07	2.01E+03
Substation foundation	Concrete	1.6E+02	m^3	6.03E+03	5.30E−01	9.88E+05	8.68E+01
	Steel bar	7.9E+00	t	5.63E+04	2.03E+00	4.45E+05	1.60E+01
Power supply	Electricity	1.8E+02	MW h	1.28E+04	2.80E−01	2.30E+06	5.04E+01
Water supply	Reservoir water	2.7E+04	t	1.33E+03	4.00E−02	3.59E+01	1.08E−03
Operation and maintenance							
Water supply	Tap water	2.6E+04	t	3.29E+03	8.00E−02	8.41E+01	2.04E−03
Blades	Resin and fibre glass	8.8E+01	t	1.88E+05	3.07E+00	1.65E+07	2.70E+02
Generators	Silica	7.2E−01	t	3.06E+04	6.00E−01	2.20E+04	4.32E−01
	Copper	7.9E+00	t	1.64E+05	4.70E+00	1.30E+06	3.72E+01
	Steel	1.7E+01	t	3.26E+04	1.39E+00	5.40E+05	2.30E+01
Disassembly and disposal							
Wind turbines						−8.26E+07	−8.69E+07
Substation						−1.18E+05	−1.24E+05

results from existing assessments of their energy and GHG intensity show considerable variations. The scatter of energy intensities is mainly due to discrepancies in (1) values for the energy content of materials, (2) the analysis scope, or breadth, and (3) the methodology, or depth of analysis [17]. Table 5 reviewed the main results of other typical research worldwide. Even after normalization with respect to lifetime and load factor, energy intensities span more than one order of magnitude from 0.040 to 0.150 MJ/MJ and the CO_2 intensity varies from 0.002 to 0.123 kg CO_2-eq/MJ (see Table 5). Compared with the study of the worldwide wind farms, the NE cost intensity of Chinese 1.25 MW wind turbines is in the median range, and the GHG emission intensity is at the lower end of the scale. Compared with other MW class wind turbines, the NE cost and GHG emission intensity of Chinese 1.25 MW wind turbines are close to that of the 3.0 MW wind turbines in Australia, and less than that of the 4.5 MW wind turbines in France and 5.0 MW wind turbines in Germany. In contrast to the small size turbines (France 250 W turbines), nonrenewable energy intensity and GHG emission intensity of the considered Chinese wind farm is one order of magnitude less. All of these facts indicate that the size of wind turbines appears to

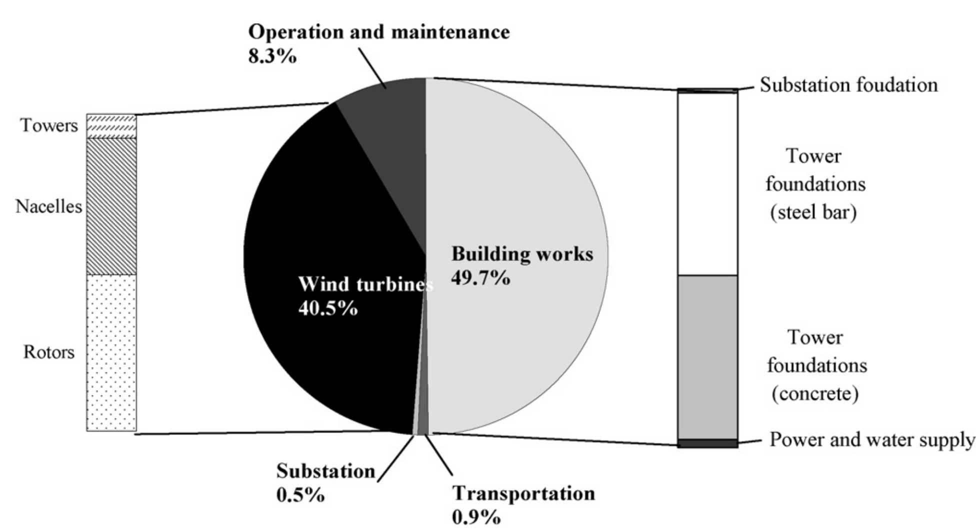

Fig. 1. NE cost fractions for a Chinese wind farm.

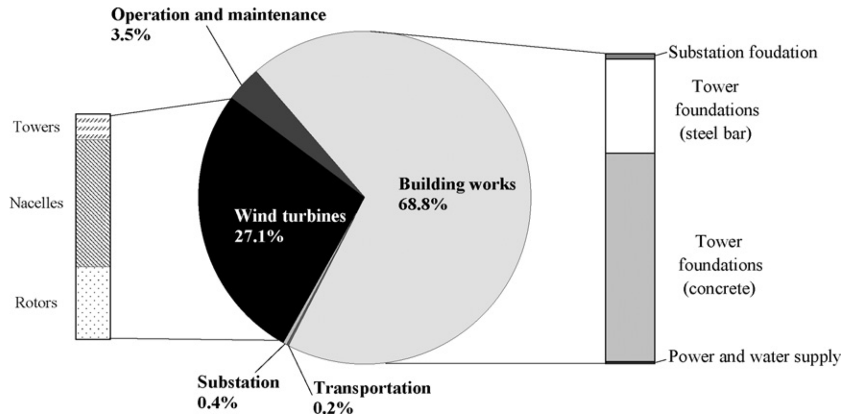

Fig. 2. GHG emission fractions for a Chinese wind farm.

Table 5
Comparison with other wind farms in the world.

Reference	Year of study	Location	Turbine type	Nonrenewable energy intensity (MJ/MJ)	GHG emission intensity (kg CO_2-eq/MJ)
This study	2010	China	1.25 MW	0.047	0.002
[22]	2009	Australia	850 kW	0.048	0.003
			3.0 MW	0.043	0.003
[21]	2009	France	250 W	0.330	0.013
			4.5 MW	0.080	0.004
[18]	2008	Germany	5.0 MW		0.006
[19]	2008	Italy	660 kW	0.040–0.070	0.002–0.004
[17]	2002	Worldwide		0.014–0.150	0.008–0.123
[23]	2010	Worldwide		0.040	0.002–0.123

be an important factor in optimizing their life cycle fossil energy cost and GHG emissions.

4.3. Comparison with coal power plants

In contrast to most renewable energy based energy systems and to wind energy systems in particular, conventional power systems and hence coal power plants also consume nonrenewable energy resources mainly during their operational life for generation of electricity. The conventional power plants just convert the fossil fuels into usable physical energy along with some inevitable losses due to thermodynamic irreversibility. Therefore, their NEIED ratio is bound to be more than unity, indicating it is a nonrenewable process. In a rough estimation, the national average coal consumptions in the generation of the thermal power plant are 356.0 g/kW h [52]. The low heat values of coal in China are 26.3 MJ/kg. The service power consumption rate in a thermal power plant is 7.1%, and the average energy line loss rate is 7.5% [52]. All of these data give a national average NEIED ratio of thermal power of 2.64 MJ/MJ. It has also been previously found that such coal power plants have a typical GHG emission coefficient of 0.22 kg CO_2-eq/MJ [53]. The coal power system therefore tends to consume about 56 times of NE and 108 times of GHG emissions as compared to the considered wind farm for per unit generation of electric power. Meanwhile, 2.59 MJ of NE and 0.218 kg CO_2-eq are saved per MJ of wind electricity output. Thus the NE saving during 20 years of operating time have been estimated at 1.22E+10 MJ, while the saved GHG emissions are 1.03E+09 kg CO_2-eq.

5. Concluding remarks

The high degree of renewability of wind power in China is illustrated by a case study of nonrenewable energy cost and greenhouse gas emission to a typical wind farm in Guangxi. The most important results of the analysis are the calculation of a total nonrenewable energy (NE) requirement of 0.047 MJ/MJ and a global warming potential of 0.002 kg CO_2-eq/MJ for the wind farm in China. Meanwhile, the energy pay back time of the considered wind farm has been calculated as 0.94 year. The research also shows that the largest NE cost and GHG emissions are mainly due to the manufacturing of components of wind turbines (rotor, nacelle, and tower) and building work. Furthermore, a general comparison of results for other wind farms in the world indicates the fossil energy cost of Chinese 1.25 MW wind turbines is at the median range, and the GHG emissions of the considered wind turbines are at the lower end of the scale. Nevertheless, it is necessary to continue investigating and raising our knowledge of wind farms, especially if we consider the huge increase and expected future growth of wind power in China. One area of special relevance is the need to reduce the NE cost and GHG emissions of the various manufacturing processes involved in producing concrete and steel bars, making the turbine and its components.

This study also proves that wind energy is a good solution to provide electricity with little fossil energy consumption, and become one of the best ways to mitigate climate change. In fact, the NE saving during 20 years of operating time have been estimated at 1.22E+10 MJ, while the saved GHG emissions are 1.03E+09 kg CO_2-eq in the designated wind farm in contrast to a coal power plant in China. Recently in China, the original goal of 30 GW installed capacities in the year 2020 has already been surpassed. In a rough estimation, if all of these installed wind turbines are in operation, the NE and GHG emission saving of 30 GW turbines during an expected life span of 20 years have been estimated to be 1.02E+13 MJ and 8.58E+11 kg CO_2-eq, respectively. The total direct GHG emission amounts to 7.46E+12 kg CO_2-eq by the commonly referred IPCC global warming potentials in China 2007 [54]. Thus Chinese total GHG emissions would be reduced by 11.5% from the baseline of 2007, if some coal power plants were substituted

by wind turbines with a capacity of 30 GW during the next 20 years.

However, the promising GHG reduction cannot be met by rapid expansion of installed wind turbines in China recently, due to the existing waste in China's large-scale wind power development [55]. Also, many experts have pointed out the low proportion between grid-connected turbines and total installed turbines [56,57]. Meanwhile, the stability of the power grid is already a problem because of weak inter-regional interconnections causing power shortages that hamper grid efficiency in different parts of the country. Existing wind farms will not be fully usable until grid upgrades are fully implemented. China requires extensive upgrades to its power grid to support newly installed wind farms in the future. Since overheated investment in wind farm development has created large-scale waste in the short term, the sustainability of such projects is brought into question. It is suggested that policy should be taken to lower the speed of building new wind farms and the current support systems should be re-elaborated to ensure a sustainable and economical development for wind power in China.

Acknowledgments

This study has been supported by the National Natural Science Foundation of China (No. 10972009). Helpful comments from Dr J.E. Coulter are appreciated.

References

[1] Chen B, Chen GQ. Resource analysis of the Chinese society 1980–2002 based on exergy. Part 2. Renewable energy sources and forest. Energ Policy 2007;35:2051–64.
[2] Yu X, Qu H. Wind power in China—opportunity goes with challenge. Renew Sust Energ Rev 2010;14:2232–7.
[3] SETC. State economic and trade commission of the People's Republic of China. Beijing: SETC; 1999 [in Chinese].
[4] Shi JL. Demonstration of wind power concession policy to reduce the large scale wind power price; 2007. Also available at: http://www.apfed.net.
[5] RRL. Renewable energy law of the People's Republic of China. The Central People's Government of the People's Republic of China; 2006 [in Chinese].
[6] CGMIA. China General Machinery Industry Association. Statistical result of installed capacity of wind power in China 2009; 2010 [in Chinese]. Also available at: http://www.cgmia.org.cn/2009/news/news.asp?vid=887.
[7] EFYP. The Eleventh Five-Year Planning. Beijing: National Development and Reform Committee of China; 2006 [in Chinese].
[8] CWEI. Wind Energy Information Center. Wind Energy Information Weekly 18; 2010 [in Chinese]. Also available at: http://wenku.baidu.com/view/4329c6ec4afe04a1b071de63.html.
[9] Xia CL, Song ZF. Wind energy in China: Current scenario and future perspectives. Renew Sust Energ Rev 2009;13:1966–74.
[10] Wall G, Gong M. On exergy and sustainable development. Part 1. Conditions and concepts. Exergy Int J 2001;1:128–45.
[11] Berthiaume R, Bouchard C, Rosen MA. Exergetic evaluation of the renewability of a biofuel. Exergy Int J 2001;1:256–68.
[12] Lems S, van der Kooi HJ, de Swaan Arons J. Quantifying technological aspects of process sustainability: a thermodynamic approach. Clean Technol Environ Policy 2003;5:248–53.
[13] Rosen MA, Dincer I. Exergy as the confluence of energy environment and sustainable development. Exergy Int J 2001;1:3–13.
[14] Yang Q, Chen B, Ji X, He YF, Chen GQ. Exergetic evaluation of corn-ethanol production in China. Commun Nonlinear Sci Numer Simulat 2009;14:2450–61.
[15] Malça J, Freire F. Renewability and life-cycle energy efficiency of bioethanol and bio-ethyl tertiary butyl ether (bioETBE): assessing the implications of allocation. Energy 2006;31:3362–80.
[16] Yang Q, Chen GQ, Chen B, Coulter J. Nonrenewable energy cost of corn-ethanol in China. Energ Policy, submitted for publication.
[17] Lenzen M, Munksgaard J. Energy and CO_2 life-cycle analyses of wind turbines—review and applications. Renew Energ 2002;26:339–62.
[18] Martin P, Oeser M, Swider DJ. Consequential environmental system analysis of expected offshore wind electricity production in Germany. Energy 2008;33:747–59.
[19] Ardente F, Beccali M, Cellura M, Brano VL. Energy performances and life cycle assessment of an Italian wind farm. Renew Sust Energ Rev 2008;12:200–17.
[20] Martínez E, Sanz F, Pellegrini S, Jiménez E, Blanco J. Life cycle assessment of a multi-megawatt wind turbine. Renew Energ 2009;34:667–73.
[21] Tremeac B, Meunier F. Life cycle analysis of 4.5 MW and 250 W wind turbines. Renew Sust Energ Rev 2009;13:2104–10.
[22] Crawford RH. Life cycle energy and greenhouse emissions analysis of wind turbines and the effect of size on energy yield. Renew Sust Energ Rev 2009;13:2653–60.
[23] Kubiszewski I, Cleveland CJ, Endres PK. Meta-analysis of net energy return for wind power systems. Renew Energ 2010;35:218–25.
[24] Chen B, Chen GQ. Ecological footprint accounting based on emergy—a case study of the Chinese society. Ecol Model 2006;198:101–14.
[25] Chen B, Chen GQ. Exergy analysis for resource conversion of the Chinese Society 1993 under the material product system. Energy 2006;31:1115–50.
[26] Chen B, Chen GQ, Yang ZF. Exergy-based resource accounting for China. Ecol Model 2006;196:313–28.
[27] Chen B, Chen GQ, Yang ZF, Jiang MM. Ecological footprint accounting for energy and resource in China. Energ Policy 2007;35:1599–609.
[28] Chen GQ, Qi ZH. Systems account of societal exergy utilization: China 2003. Ecol Model 2007;208:102–18.
[29] Chen B, Chen GQ. Modified ecological footprint accounting and analysis based on embodied exergy—a case study of the Chinese society 1981–2001. Ecol Econ 2007;61:355–76.
[30] Chen GQ, Chen B. Resource analysis of the Chinese society 1980–2002 based on exergy. Part 1. Fossil fuels and energy minerals. Energ Policy 2007;35:2038–50.
[31] Ji X. Ecological accounting and evaluation of urban economy: taking Beijing city as the case. Commun Nonlinear Sci Numer Simulat 2010, doi:10.1016/j.cnsns.2010.05.034.
[32] Chen B, Chen GQ. Resource analysis of the Chinese Society 1980–2002 based on exergy. Part 3. Agricultural products. Energ Policy 2007;35:2065–78.
[33] Chen B, Chen GQ. Resource analysis of the Chinese Society 1980–2002 based on exergy. Part 4. Fishery and rangeland. Energ Policy 2007;35:2079–86.
[34] Chen GQ, Chen B. Resource analysis of the Chinese society 1980–2002 based on exergy. Part 5. Resource structure and intensity. Energ Policy 2007;35: 2087–95.
[35] Jiang MM, Zhou JB, Chen B, Chen GQ. Emergy-based ecological account for the Chinese economy in 2004. Commun Nonlinear Sci Numer Simulat 2008;13:2337–56.
[36] Chen GQ, Chen B. Extended-exergy analysis of the Chinese society. Energy 2009;34:1127–44.
[37] Chen GQ, Jiang MM, Yang ZF, Chen B, Ji X, Zhou JB. Exergetic assessment for ecological economic system: Chinese agriculture. Ecol Model 2009;220: 397–410.
[38] Jiang MM, Zhou JB, Chen B, Yang ZF, Ji X, Zhang LX, et al. Ecological evaluation of Beijing economy based on emergy indices. Commun Nonlinear Sci Numer Simulat 2009;14:2482–94.
[39] Chen GQ, Chen ZM. Carbon emissions and resources use by Chinese economy 2007: a 135-sector inventory and input–output embodiment. Commun Nonlinear Sci Numer Simulat 2010;15:3647–732.
[40] Chen H, Chen GQ, Ji X. Cosmic emergy based ecological systems modeling. Commun Nonlinear Sci Numer Simulat 2010;15:2672–700.
[41] Chen ZM, Chen GQ, Zhou JB, Jiang MM, Chen B. Ecological input–output modeling for embodied resources and emissions in Chinese economy 2005. Commun Nonlinear Sci Numer Simulat 2010;15:1942–65.
[42] Zhang B, Chen GQ. Physical sustainability assessment for the China society: exergy-based systems account for resources use and environmental emissions. Renew Sust Energ Rev 2010;14:1527–45.
[43] Yang ZF, Jiang MM, Chen B, Zhou JB, Chen GQ. Solar emergy evaluation for Chinese economy. Energ Policy 2010;38:875–86.
[44] Cleveland CJ. Net energy analysis. In: Cleveland CJ, editor. Encyclopedia of earth. New York: Elsevier Publishing Company; 2007. Also available at: http://www.eoearth.org/article/Net_energy_analysis.
[45] Chen H, Chen GQ. Energy cost of rapessed-based biodiesel as alternative energy in China. Renew Energ 2011;36:1374–8.
[46] Sheehan J, Camobreco V, Duffield J, Graboski M, Shapouri H. Life cycle inventory of biodiesel and petroleum diesel for use in an urban bus. Final report. Golden, CO: National Renewable Energy Laboratory; 1998.
[47] Zhou JB. Embodied ecological elements accounting of national economy. PhD dissertation. Peking University, Beijing, China; 2008 [in Chinese].
[48] Zhao YH. Feasibility report of Yulin wind farm project. Beijing, China: China Hua Dian Corporation; 2008 [in Chinese].
[49] Young S, Dubreuil A, Stewart M. Qualitative maps of metal recycling. Draft report. London, UK: International Council on Mining & Metals; 2006.
[50] Zhu W. The reclaimation methodologies of the waste computer boards and blocks. Master thesis. Nanjing University of Science and Technology, Nanjing, China; 2004 [in Chinese].
[51] GER. Grupo Eólicas Riojanas. Proyecto de desmantelamiento del parque eólico de Munilla – Lasanta; 2004.
[52] CESY. China energy statistical yearbook. Beijing: China Statistics Press; 2003 [in Chinese].
[53] Yang Q, Chen GQ. Greenhouse gas emissions and fossil fuel cost of corn-ethanol production in China. Energ Policy, submitted for publication.
[54] Chen GQ, Zhang B. Greenhouse gas emissions in China 2007: inventory and input–output analysis. Energ Policy 2010;38:6180–93.
[55] Rutkowski R. China's wind power has faulty connection. Asia Times; 2010. Also available at: http://www.atimes.com/atimes/China_Business/LF16Cb03.html.
[56] Bai Na Net. Installed capacity of wind turbines increases rapidly with low grid-connected proportion in China; 2010 [in Chinese]. Also available at: http://www.ic98.com/info/jixie/82/2010524/90435.Html.
[57] Li J. Decarbonising power generation in China—is the answer blowing in the wind? Renew Sust Energ Rev 2010;14:1154–71.

G.Q. Chen is a professor of in College of Engineering at Peking University. He is also a standing council member of China Energy Society. He obtained B.E. and M.S. degrees in thermal power engineering from Huazhong University of Science and Technology, and Ph.D. degree in fluid mechanics from Peking University. Prior to his current positions, Prof. Chen had been serving as a visiting professor in the University of Pittsburgh and the University of Hong Kong. Prof. Chen published over 100 peer-reviewed papers in prestigious international journals such as *Renewable and Sustainable Energy Reviews*, *Energy Policy, Energy*, *Journal of Heat Transfer*, *Journal of Computational Physics, Ecological Economics, Ecological Engineering,* and *Ecological Modeling*. At least eight of his papers have been indexed in Elsevier/ScienceDirect Top 25 Hottest Articles. He also edited, co-edited, authored, and co-authored several books and book chapters. With distinguished contributions to his fields, Prof. Chen has won a series of awards and honors, including Award of Elsevier Economics Journals Most Cited Articles, the 1st Prize of Zhou Pei-Yuan CAST Outstanding Paper Award in Hydrodynamics. As an active and renowned researcher in academic fields, he served or is serving as the editor-in-chief of *Communications in Nonlinear Science and Numerical Simulation*, an associate editor of *Journal of Hydrodynamics and Research* and *Progress in Hydrodynamics*, and an editorial board member of *Energy Policy*, *Ecological Indicators*, *Journal of Mathematical Control and Applications*, *International Journal of Nonlinear Science and Numerical Simulation*, *International Journal of Applied Engineering Research*, *Mechanics of Multi-Component Materials*, and *Frontiers of Earth Science in China*. He was also among the organizers and keynote speakers for various international conferences.